EFFECTS OF APPLICATION METHOD AND RATE OF LIQUID STARTER FERTILIZER ON MAIZE GROWTH AND YIELD
/
液态起始肥施肥方式及施肥量对玉米生长及产量的影响

Changchang YU, Qiming DING, Zhan HE, Qianyi WANG, Xuewen LIU, He LI*
College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou 450002, China
Tel: +86-13391727083; E-mail: yuchang@henau.edu.cn
Corresponding author: He LI
DOI: https://doi.org/10.35633/inmateh-77-21

***Keywords:** liquid starter fertilizer, fertilization, application method, maize growth, maize yield and yield components*

ABSTRACT
Liquid fertilizers have gained widespread use owing to their higher nutrient use efficiency, improved nutrient uptake, and reduced environmental impact. However, the agronomic effects of different application methods and rates of liquid fertilizer on maize growth and yield remain insufficiently investigated. This study conducted a two-year field experiment to evaluate the effects of four fertilizer application methods: band application of granular fertilizer (BAGF), mixed hole application of liquid fertilizer (MHALF), side hole application of liquid fertilizer (SHALF), and a control treatment without starter fertilizer (CK). Four liquid fertilizer rates (45, 105, 150, and 300 kg/ha) were tested. The results indicated that the application method plays a critical role in determining maize emergence and early growth. In particular, SHALF at moderate rates (45 and 105 kg/ha) significantly improved emergence rate, dry matter accumulation, and plant height compared with MHALF and BAGF. In contrast, high fertilizer rates (150 and 300 kg/ha) in MHALF treatments negatively affected emergence rate. Fertilizer treatments also had a significant effect on maize yield and its components. The SHALF treatment at a rate of 150 kg/ha resulted in an average yield increase of 4.9% compared with CK. These findings suggest that a moderate rate of SHALF is a practical and effective strategy for improving maize productivity in cold temperate regions.

摘要
液体肥料因其更高的养分利用率、更易吸收和更少的环境影响而被广泛应用，然而，不同施肥方式和施用量对玉米生长和产量的农艺效应仍未得到充分研究。本研究开展了为期两年的田间试验，评估了四种施肥方式：颗粒肥条施（BAGF）、液体肥料混合穴施（MHALF）、液体肥料侧深穴施（SHALF）以及不施肥的对照处理（CK），以及四种施肥量（45、105、150 和 300 kg/ha）对玉米生长与产量的影响。结果表明，液体肥料施用方式对玉米出苗和早期生长起着重要作用。与 MHALF 和 BAGF 相比，中等施肥量（45 和 105 kg/ha）的 SHALF 显著提高了出苗率、干物质质量和株高，相反，MHALF 处理中较多的施肥量（150 和 300 kg/ha）对出苗率有负面影响。施肥处理对玉米产量及其构成因素也有显著影响，在施肥量为 150 kg/ha 时，SHALF 处理平均比 CK 增产 4.9%。结果表明， SHALF 和中等施肥量是寒温带地区提高玉米产量的有效策略。

INTRODUCTION
Maize (Zea mays L.) is one of the most widely cultivated and commercially traded cereal crops globally. It serves as a critical source of food, livestock feed, industrial raw materials, and energy, with its consumption and demand are steadily increasing worldwide *(Assefa et al., 2019; Blandino et al., 2022; Cassman et al., 2003)*. Since the early 21st century, global maize productivity and yield have increased by 30%. This agricultural progress can largely be attributed to the cultivation of improved varieties, early planting dates, optimized agronomic practices, fertilizer application, and the adoption of mechanization. In particular, fertilizer application has contributed to about 20% of the yield improvement in maize *(Bindraban et al., 2018; Li et al., 2021; Wang et al., 2024)*. China, as the world's largest producer and consumer of fertilizers, has experienced a significant decline in total fertilizer use and application intensity since 2015. However, annual fertilizer consumption exceeds 50 million tons, with utilization efficiency ranging from 30% to 40% *(Li et al., 2017; Shi et al., 2016)*. Excessive fertilizer use has led to nutrient loss, reduced efficiency, water eutrophication, soil compaction and acidification, decreased fertility, increased greenhouse gas emissions, compromised agricultural product quality, and environmental pollution *(Leslie et al., 2017; Dimkpa et al., 2020; Tian et al.,*

2024; Liu, 2017). These challenges highlight the need for strategies to improve fertilizer utilization efficiency and reduce environmental impact, especially in maize production systems *(Van Wesenbeeck et al., 2021; Ocwa et al., 2023)*.

In the single-cropping zone of Northeast China, which is characterized by a cold temperate climate, advancing the spring planting date is crucial for improving maize yield. This approach extends the crop's growing period, potentially increasing yield and enhancing grain quality. However, early planting can expose seedlings to cold stress, which limits root nutrient uptake and restricts growth *(Capo et al., 2024)*. An effective approach to mitigate this stress is the application of starter fertilizer, which promotes root system development and enhances critical growth parameters (plant height, biomass accumulation, and leaf expansion) in low-temperature root zones during early spring *(Imran et al., 2013)*. In Northeast China, farmers typically apply basal fertilizer in a single application at planting, along with a minimal rate of starter fertilizer *(Cai et al., 2012)*.

Starter fertilizer, typically placed near seeds during sowing, ensures a concentrated supply of phosphorus and other essential nutrients, stimulating early plant vigour and ensuring uniform maize growth *(Rehm et al., 2009)*. This approach secures nutrient availability during critical early growth stages, particularly in stressful environments with limited root exploration *(Battisti et al., 2023; Battisti et al., 2022; Chen et al., 2024)*. Previous studies have shown that starter fertilizer has a positive influence on maize yield and nutrient absorption. Herrmann et al. reported that the application of starter fertilizer increased maize yield by 9.4% while improving phosphorus use efficiency *(Herrmann et al., 2024)*. Quinn et al. examined its impact on maize yield in the United States and found a 5.2% increase, along with improved root utilization of soil nutrient pools and alleviation of early-season localized nutrient deficiencies *(Quinn et al., 2020)*. Additionally, starter fertilizer applications have demonstrated beneficial effects on several less-studied vegetable crops *(Nkebiwe et al., 2016)*.

The placement of starter fertilizers plays a significant role in nutrient absorption. Traditional starter fertilizer application methods include band or hole placement, typically using specialized granular phosphate fertilizers *(Kaiser et al., 2016)*. In China, starter fertilizer is usually placed in the same furrow as the seed during planting. While the root zone is the primary site for nutrient uptake, maize root development is limited during early growth, restricting access to nutrients between adjacent plants. This inefficiency in nutrient uptake leads to reduced fertilizer utilization, while excess nutrients are lost through runoff and volatilization, contributing to groundwater contamination and air pollution *(Ye et al., 2010)*. Hole application involves placing a precise rate of fertilizer in targeted locations near the maize root zone, thereby ensuring efficient nutrient uptake and enhancing fertilizer utilization efficiency and maize productivity *(Guo et al., 2020)*. Shi et al. reported that hole application increased average maize yield by 8.5% and nitrogen recovery efficiency by 23.3% over three years compared to band application *(Shi et al., 2020)*. Jiang et al. demonstrated that a one-time hole application of urea in the root zone of summer maize increased yield by 9.8% compared to band treatment. It significantly increased nitrogen and phosphorus utilization rates by 12.4% and 27.2%, respectively *(Jiang et al., 2018)*. Zhou et al. compared one-time root zone hole application with in-furrow strip application under mulch in summer maize, reporting a 4.98% increase in straw and seed dry matter content and a 30.61% higher nitrogen fertilizer utilization rate *(Zhou et al., 2020)*. Additionally, Hui et al. also highlighted the significant effects of hole application on soil microenvironments, crop growth, and yield parameters. Compared to band application, maize yield increased by 28.4%. These findings collectively underscore the potential of hole application to enhance fertilizer utilization efficiency, increase maize productivity, and promote sustainable agricultural practices *(Chen et al., 2024)*.

Implementing novel fertilizer varieties is also an effective strategy to reduce chemical fertilizer consumption and enhance utilization efficiency. In recent years, liquid fertilizers have gained widespread adoption in agriculture worldwide. Compared to granular fertilizers, liquid fertilizers require less energy to produce and are more cost-effective. They offer key advantages such as faster nutrient absorption, higher nutrient use efficiency, and low environmental impact *(Kasal et al., 2015; Silva et al., 2017; Yu et al., 2019)*, making them increasingly popular. Recently, the hole application of liquid starter fertilizer near plants or seeds has gained attention. Some studies have shown that appropriate methods for applying liquid starter fertilizer can reduce fertilizer use by 30% without compromising production *(Drazic et al., 2020; Yu et al., 2021)*. Despite growing interest in the use of liquid fertilizers and advancements in precision application technologies, a critical gap remains in agronomic research evaluating how different application methods and rates of liquid starter fertilizers affect maize performance under field conditions. Most previous studies have emphasized engineering innovations, such as variable-rate application systems and the simultaneous sowing system for seed and fertilizer, while giving limited attention to agronomic outcomes *(Zhou et al., 2023; Gao et al., 2023; Liang et al., 2024)*. Therefore, this study was conducted to evaluate the impacts of different liquid starter fertilizer application methods (band vs. hole) and rates on maize growth and yield under field conditions in Northeast China. Specifically, the study focuses on growth indicators such as emergence rate, dry matter mass, and plant height, as well as yield metrics including total yield, 1000-grain weight, spikes per hectare, and grains per spike. It is hypothesized that: (1) hole application of liquid starter fertilizer near the maize root zone significantly enhances emergence rate, early growth, and maize yield compared with traditional band application, and (2) a moderate application rate of liquid starter fertilizer optimizes fertilizer use efficiency without compromising yield.

Thus, the objectives of this study were to: (1) compare the agronomic performance of hole versus band applications of liquid starter fertilizer, and (2) evaluate the effects of different application rate on maize emergence, growth, and yield. This study aims to extend current understanding by demonstrating the improved fertilizer utilization efficiency and yield-related advantages of hole application of liquid starter fertilizer in maize production, particularly in cold temperate regions such as Northeast China.

MATERIALS AND METHODS

Experimental Site

The research was conducted in Moshutun Village, Shenbei New District, Shenyang City, Liaoning Province, China (42.01°N, 123.46°E). The region has a continental monsoon climate within the northern temperate zone, with annual average temperatures ranging from 6.2°C to 9.7°C. The average annual precipitation is 755.4 mm, spread across 93.8 days of rainfall. The mean temperature and precipitation in the growing seasons included in the experiment is shown in Figure 1. The soil at the experimental site was a brown soil, classified as a Stagnic Luvisol (Loamic, Endoloamic) according to the World Reference Base for Soil Resources (WRB, 4th edition) *(Mantel et al., 2022)*. The top soil layer (0-20 cm) before sowing had a bulk density of 1.44 g cm^{-3}, a pH of 5.58, 68.2 g kg^{-1} organic matter, 1.34 g kg^{-1} total nitrogen, 49 mg kg^{-1} available phosphorus, and 221 mg kg^{-1} available potassium. The experimental area follows an annual maize cropping system with conservation tillage. Maize is planted from April to May and harvested in October each year. After harvest, maize straw is fully returned to the field, and no-till planters are used for sowing in the subsequent year.

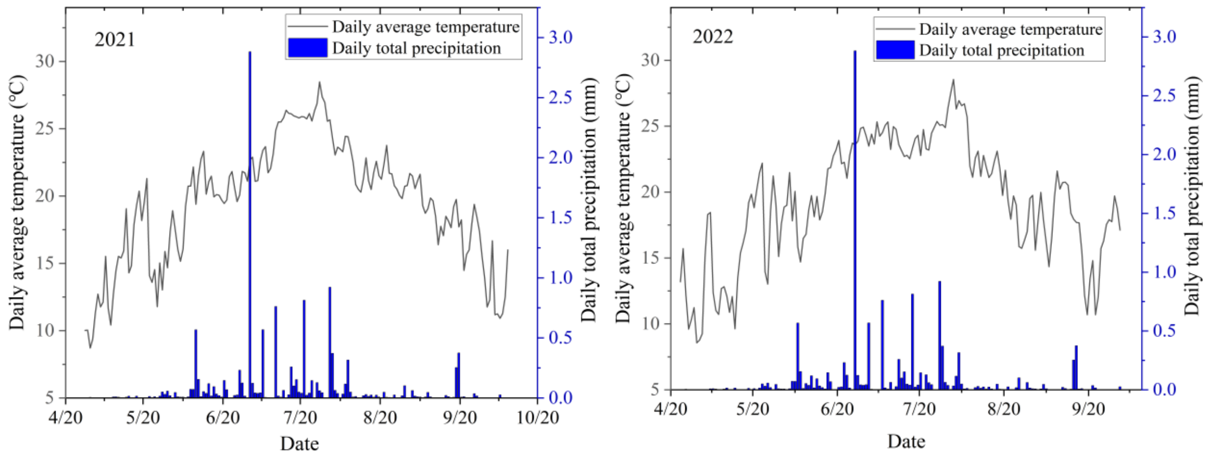

Fig. 1 - Daily total precipitation and average temperature at the experimental site during the maize growing seasons in 2021 and 2022

Experimental Design and Field Management

A randomized complete block design (RCBD) was used to evaluate the effects of various placements and application rates on maize emergence, growth, and yield. The experiment consisted of 10 distinct fertilization treatments, arranged in a factorial structure combining four application methods with four fertilizer rates. Each treatment was replicated three times across blocks to account for field variability. The experimental plots measured 80 meters in length and 6 meters in width, with the central 60 meters designated as the sampling area to minimize edge effects. The experimental treatments were designed as follows: (1) CK: Starter fertilizer was not applied during planting. Only basal fertilizer was applied via deep placement (0.08 m below and 0.08 m to the side of the seed row).

The rate of basal fertilizer was 750 kg/ha; (2) BAGF: Basal fertilizer (750 kg/ha) was applied the same to CK treatment. Granular starter fertilizer (150 kg/ha) was applied in bands in the furrows during seed planting; (3) MHALF: Basal fertilizer (750 kg/ha) was applied the same to CK treatment. Seeds and liquid fertilizer were applied simultaneously in the furrow. The liquid fertilizer created distinct "spots" along the seed furrows, with maize seeds positioned centrally within these fertilizer areas. Direct interaction between seeds and fertilizer increased salt concentration, requiring stringent dosage regulation to prevent seed damage *(Hajabbasi et al., 1994)*. The liquid fertilizer was applied at four levels: 30% (MHALF30), 70% (MHALF70), 100% (MHALF 100), and 200% (MHALF 200) of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; (4) SHALF: Basal fertilizer (750 kg/ha) was applied the same to CK treatment. Liquid starter fertilizer was positioned 0.05 m to the side of each seed. The liquid fertilizer was applied at the four levels: 30% (SHALF30), 70% (SHALF70), 100% (SHALF100), and 200% (SHALF200) of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively. The Details of the treatment are illustrated in Figure 2.

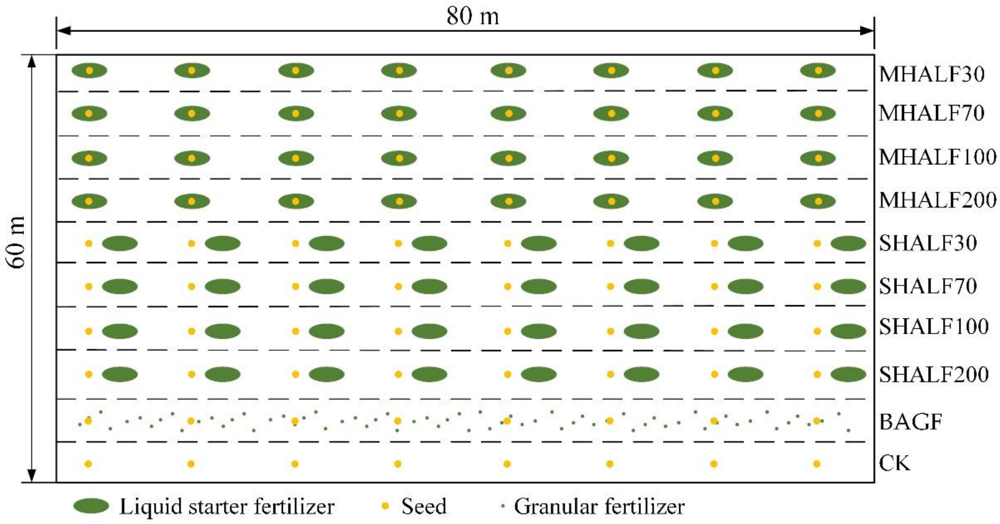

Fig. 2 - Schematic diagram of the experimental trial.

CK: control treatment with no starter fertilizer; BAGF: band application of granular fertilizer; MHALF30, MHALF70, MHALF100, and MHALF200 represent the mixed hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; SHALF30, SHALF70, SHALF100, and SHALF200 represent the side hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively.

The maize variety used in this study was Liaodan 575, developed by the Corn Research Institute of the Liaoning Academy of Agricultural Sciences. Maize was planted with a row spacing of 0.6 m and a plant spacing of 0.28 m, resulting in a sowing density of 59550 plants per hectare. Crystalline diammonium phosphate (N: P_2O_5 = 21%: 53%) was dissolved in water as the liquid fertilizer, which was manufactured by Kanglong Chemical Co., Ltd. in Shifang City. The rate of liquid fertilizer for hole fertilization was set at 5 mL per operation. Different fertilization levels were achieved by dissolving varying quantities of crystalline diammonium phosphate in water. Granular fertilizer used diammonium phosphate (N: P_2O_5 = 18%: 46%), produced by Yun-tianhua Fertilizer Co., Ltd. in Yunnan Province. Basal fertilizer consisted of compound fertilizer (N: P_2O_5: K_2O = 28%: 5%: 5%) from Liaoning Yuheng Fertilizer Technology Co., Ltd., with an application rate of 750 kg/ha. The maize was planted on April 28 and harvested on October 10 in 2021, and planted on April 24 and harvested on October 2 in 2022. All other field management practices were consistent with standard production fields.

Sample Collection and Measurements

Emergence Rate

The emergence rate refers to the percentage of maize seeds that successfully emerged from the soil surface within seven days after sowing. It reflects the early establishment ability of maize plants in field conditions *(Liu et al., 2025)*. The five-point sampling method was employed on the seventh day after sowing to determine the maize emergence rate within the experimental plots. Five evenly distributed sampling points were selected in each plot, and the number of emerged seedlings was recorded. The emergence rate was calculated using the following formula:

$$R_s = \frac{n_g}{n_t} \times 100\% \tag{1}$$

where: R_s is the maize emergence rate (%), n_g is the number of emerged seedlings within 7 days, and n_t is the total number of tested seeds.

Dry Matter Mass

On the 25th day (seedling stage) and 51st day (jointing stage) after sowing, 10 representative maize plants were randomly selected from each treatment. The maize plants were carefully uprooted to ensure the roots remained intact. The roots were then severed at the stem base, and the fresh weight of the plants was immediately recorded. Subsequently, the processed maize plants were placed in clean, dry envelopes and transferred to an oven (Shanghai Bilang Instrument Manufacturing Co., Ltd., model DHG-9420A). The samples were first deactivated at 105°C for 30 minutes, followed by drying at 80°C until a constant weight was achieved. The dry matter mass was then recorded.

Plant Height

On the 25th day (seedling stage) and 51st day (jointing stage) after sowing, 10 consecutive maize plants were randomly selected from each treatment. Plant height was measured using a tape measure (Shanghai Chenguang Stationery Co., Ltd., model AHT99101), recording the distance from the soil surface to the highest point of the maize plant.

Maize Yield and Yield Components

After maturity, the five-point sampling method was employed to determine maize yield under different fertilization treatments *(Yang et al., 2024)*. The maize yield was calculated using the following formula:

$$Q_c = \frac{G_s N_m N_s}{10^6} \tag{2}$$

where: Q_c is the maize yield (kg/ha), G_s is the 1000-grain weight at standard moisture content (g), N_m is the spikes per hectare, and N_s is the grains per spike. As shown in Equation 2, the main factors affecting maize yield are standard moisture 1000-grain weight, spikes per hectare, and grains per spike.

The procedure to determine the 1000-grain weight at standard moisture is as follows: First, the maize sample is threshed, and the weight of 1000 grains is measured under natural moisture content. Then, the maize is placed in an oven and dried for 2 hours at 105°C, followed by adjusting the temperature to 80°C and drying for another 4 hours until the maize reaches a constant weight. The actual moisture content of the maize is then determined.

The 1000-grain weight at standard moisture is calculated after converting the actual moisture content to the standard moisture content of maize.

$$G_s = \frac{G_n \times (100 - M_a)}{100 - M_s} \tag{3}$$

where: G_n is the 1000-grain weight at standard moisture (g), M_a is the actual moisture of grains (%); and M_s is the standard moisture (%). According to the China National Standards GB1353-2009, the standard moisture content is 14%.

The formula for calculating spikes per hectare is:

$$N_m = \rho_s \times (1 + \rho_d - \rho_e) \tag{4}$$

where: ρ_s is sowing density (spikes per hectare), ρ_e is the barren stalk rate (%), ρ_d is the double-spike rate (%).

The barren stalk and double-spike rates were measured as follows: Three representative maize rows were selected in the experimental plots. A continuous sequence of 100 maize plants was surveyed to count barren stalks and double-spike plants. Maize plants with fewer than 20 grains per spike were classified as barren stalks, while double-spike plants were excluded from the barren stalk rate calculation. The barren stalk and double-spike rates were expressed as percentages of the total surveyed plants. A continuous sequence of 21 maize plants was randomly selected for sowing density. The total distance between the first and 21st plants was measured. The average plant spacing and row spacing were derived by dividing the total distance by 20. Sowing density was calculated as follows.

$$\rho_s = \frac{1}{l_s d} \times 10^4 \tag{5}$$

where: l_s is the row spacing of maize (m), and d is the plant spacing of maize (m).

The method for determining the grains per spike was as follows: A sample of 20 consecutive maize plants was selected. The number of grains per row and the number of grains row on each spike were measured separately. The number of grains row was determined by counting the rows in the middle section of the sampled spike. The grains per row were counted from a row of medium length. The total number of grains per spike was then calculated using the following formula:

$$N_s = N_c \times N_r \tag{6}$$

where: N_a is the number of grains per spike, N_c is the number of grains per row, and N_r is the number of grain rows per spike.

Statistical Analysis

A two-way analysis of variance (ANOVA) in the General Linear Model module of SPSS Statistics 26 (SPSS Inc., Chicago, IL, USA) was conducted to examine the effects of fertilization treatment, year, and their interactions on maize emergence, growth, and yield under investigation. Multiple comparisons between treatments were conducted using the Waller-Duncan method, with significance determined at P < 0.05. Graphs were generated using OriginPro 2018.

RESULTS AND DISCUSSION

Emergence Rate

As shown in Table 1, analysis of variance revealed that fertilization treatment had a significant effect on maize emergence rate (P<0.01), whereas the effects of year and the interaction between year and treatment were not significant. Figure 3 illustrates the maize emergence rate under different fertilizer treatments in 2021 and 2022. The emergence rate of BAGF and MHALF30 was not significantly different from CK in both 2021 and 2022. However, the emergence rates of MHALF100 and MHALF200 were significantly different, with the average reduction of 10.3% and 12.4%, respectively, compared to CK. The emergence rate of MHALF70 showed a significant difference in 2022, but not in 2021.

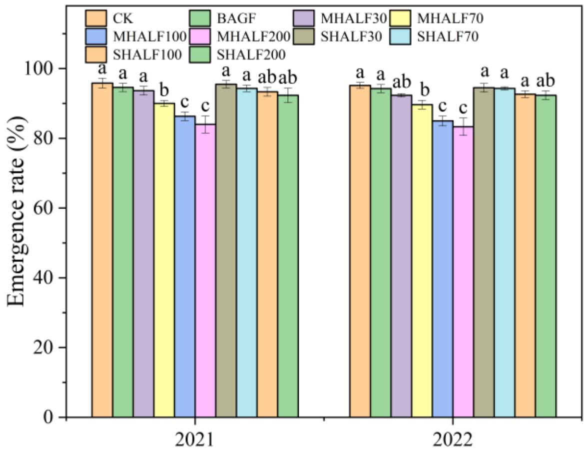

Fig. 3 - Maize emergence rate under different fertilization treatments in 2021 and 2022

CK: Control treatment with no starter fertilizer; BAGF: Band application of granular fertilizer; MHALF30, MHALF70, MHALF100, and MHALF200 represent the mixed hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; SHALF30, SHALF70, SHALF100, and SHALF200 represent the side hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively. Different letters above the bars indicate significant differences among treatments according to the Waller-Duncan test (P < 0.05).

These results indicate that the mixed hole application of liquid fertilizer can affect seed germination, with the inhibitory effect becoming more pronounced as the fertilizer rate increases. Therefore, it is important to avoid direct contact between seeds and fertilizer. For the treatment of side hole liquid starter fertilizer, the emergence rates SHALF30 and SHALF70 showed no significant difference compared to CK, both in 2021 and 2022. However, the emergence rates of SHALF200 showed a significant difference, with an average decrease of 3.3% compared to CK. SHALF100 showed a significant difference in 2021, but not in 2022.

These results indicate that the fertilizer rate influences the emergence rate when using side hole application of liquid starter fertilizer. At low fertilizer levels (SHALF30, SHALF70), the maize emergence rate remains largely unaffected, while at higher levels (SHALF100, SHALF200), the emergence rate is slightly reduced, although the decrease is minimal. When the fertilizer rate was the same, the emergence rate of MHALF30 was not significantly different from that of SHALF30 in both 2021 and 2022. However, the emergence rates of MHALF70, MHALF100, and MHALF200 were, on average, 4.8%, 7.9%, and 9.4% lower, respectively, than those of SHALF70, SHALF100, and SHALF200. This indicates that the emergence rate is influenced by the application method of liquid starter fertilizer, and SHALF performs better than MHALF. The reduced emergence rate of MHALF may be attributed to the proximity or direct contact between seeds and fertilizers. Nutrients such as nitrogen in the fertilizer can inhibit seed germination and early root development. As the fertilizer application rate increases, the inhibitory effect becomes more severe, potentially leading to seed burn and lower emergence rates. The liquid starter fertilizer (N: P_2O_5 = 21%: 53%) used in this study contains nitrogen in forms that can cause salt or ammonia damage when applied close to the seeds. High concentrations of nitrogen, particularly in liquid form, can lead to osmotic stress or ammonia toxicity, both of which inhibit seed germination and early root growth. Additionally, the emergence rate of SHALF100 was not significantly different from BAGF, while the emergence rate of MHALF100 was 8.7% lower than BAGF.

Table 1

Results of the analysis of variance (ANOVA) evaluating the effects of year (Y), fertilization treatment (T), and their interaction (Y×T) on maize emergence rate, dry matter mass, and plant height at different growth stages. **, significant at P<0.01; *, significant at P<0.05; ns, not significant.

	Emergence rate	Dry matter mass at seedling stage	Dry matter mass at jointing stage	Plant height at seedling stage	Plant height at jointing stage
Year (Y)	ns	ns	**	*	**
Treatment (T)	**	*	**	**	**
Y×T	ns	ns	ns	ns	ns

Dry Matter Mass

As shown in Table 1, the analysis of variance revealed that fertilization treatment had a significant effect on dry matter mass at both the seedling stage ($P < 0.05$) and the jointing stage ($P < 0.01$). Year had a significant effect only at the jointing stage ($P < 0.01$), whereas the effect of year at the seedling stage and the interaction between year and treatment were not significant. The dry matter mass of maize at different growth stages and treatments in 2021 and 2022 is shown in Figure 4.

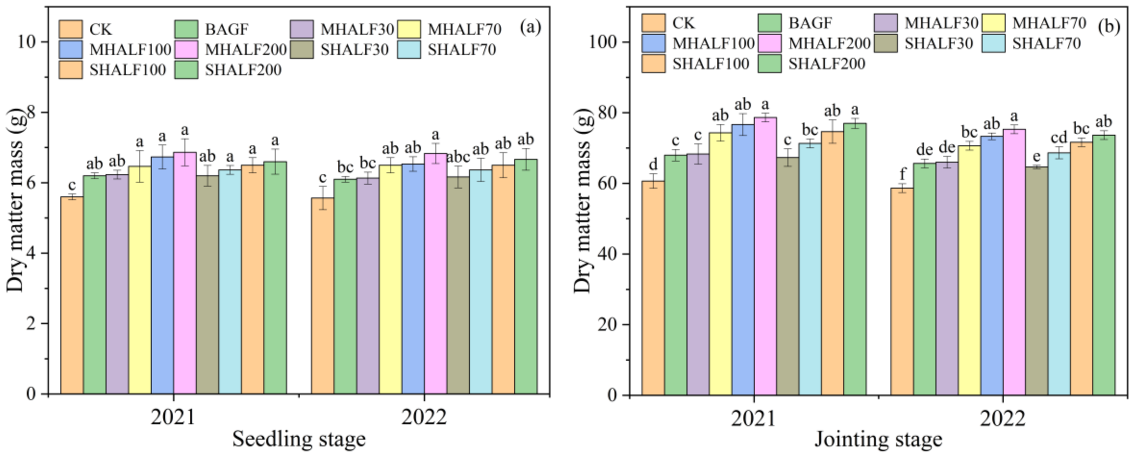

Fig. 4 - Dry matter mass of maize under different fertilization treatments at the seedling stage (a) and jointing stage (b) in 2021 and 2022

CK: Control treatment with no starter fertilizer; BAGF: Band application of granular fertilizer; MHALF30, MHALF70, MHALF100, andMHALF200 represent the mixed hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; SHALF30, SHALF70, SHALF100, and SHALF200 represent the side hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively. Different letters above the bars indicate significant differences among treatments according to the Waller-Duncan test (P < 0.05).

At the seedling stage (Figure 4a), the application of starter fertilizer significantly affected the dry matter accumulation of maize's aboveground part. Compared to CK, the average dry matter weight of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 increased by10.1%, 10.7%, 16.1%, 18.8%, 22.7%, 10.7%, 14.0%, 16.4% and 18.8%, respectively. For the treatment of mixed hole liquid starter fertilizer, the dry matter masses of MHALF70, MHALF100, and MHALF200 were significantly higher than that of MHALF30, with average increases of 4.3%, 7.6%, and 10.5%, respectively. No significant difference was observed between MHALF70, MHALF100, and MHALF200 in 2021.

However, in 2022, MHALF200 showed a significant difference compared to both MHALF70 and MHALF100. Overall, the dry matter mass increased significantly when the fertilizer rate was less than 105 kg/ha, but there was no significant difference when the rate exceeded 105 kg/ha per plant. For the treatment of side hole liquid starter fertilizer, SHALF70, SHALF100, and SHALF200 had significantly higher dry matter mass than SHALF30, with average increases of 2.8%, 5.0%, and 6.9%, respectively. No significant difference was found between SHALF70, SHALF100, and SHALF200 in both 2021 and 2022. It indicates that the dry matter mass increased significantly when the fertilizer rate was less than 105 kg/ha. However, there was no significant difference when the rate exceeded 105 kg/ha. When the fertilizer rate was the same, no significant differences were observed between MHALF30, MHALF70, MHALF100, MHALF200 and SHALF30, SHALF70, SHALF100, and SHALF200 in 2021. MHALF70 and MHALF100 also showed no significant difference compared to SHALF70 and SHALF100 in 2022. However, MHALF30 and MHALF200 had significant differences from SHALF30 and SHALF200, with decreases of 0.5% and 2.5%, respectively. Furthermore, the dry matter mass of MHALF100 and SHALF100 was significantly higher than that of BAGF, with average increases of 7.9% and 5.7%, respectively.

At the jointing stage (Figure 4b), the application of starter fertilizer had a significant effect on the dry matter accumulation of maize's aboveground part in both 2021 and 2022. Compared to CK, the dry matter mass of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 increased by 12.0%, 12.6%, 21.5%, 25.7%, 29.1%, 10.6%, 17.3%, 22.6%, and 26.3%, respectively. All treatments for mixed hole liquid starter fertilizer exhibited significant differences in 2022. In 2021, MHALF100 and MHALF200 significantly differed from MHALF30 and MHALF70. It indicates that the rate of liquid fertilizer can affect dry matter mass with a positive correlation. For the treatment of side hole liquid starter fertilizer, SHALF30, SHALF70, SHALF100, and SHALF200 had significantly different dry matter masses in both 2021 and 2022, indicating that the fertilizer rate had a pronounced effect on maize dry matter accumulation, with dry matter weight generally increasing as fertilizer levels increased. When the fertilizer rate s were the same, the dry matter mass of MHALF70 was 4.2% higher than that of SHALF70, while MHALF30, MHALF100, and MHALF200 showed no significant differences compared to SHALF30, SHALF100, and SHALF200 in 2021. In 2022, MHALF30, MHALF30, MHALF100, and MHALF200 were significantly difference from SHALF30, SHALF70, SHALF100, and SHALF200, with increases of 2.1%, 2.9%, 2.3% and 2.3%, respectively. The treatment of MHALF could promote the accumulation of dry matter mass more effectively than SHALF. Additionally, the dry matter mass of MHALF100 and SHALF100 was significantly higher than that of BAGF, with average increases of 12.2% and 9.5%, respectively.

Plant Height

As shown in Table 1, the analysis of variance revealed that fertilization treatment had a significant effect on plant height at both the seedling stage and the jointing stage ($P < 0.01$). Year also had a significant effect at the seedling stage ($P < 0.05$) and the jointing stage ($P < 0.01$), whereas the interaction between year and treatment was not significant. The plant height of maize at different growth stages and treatments in 2021 and 2022 is shown in Figure 5. At the seedling stage (Figure 5a), the application of starter fertilizer significantly influenced plant height. Compared to CK, the plant heights of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 average increased by 22.2%, 17.2%, 23.1%, 25.8%, 30.8%, 8.9%, 16.8%, 24.3%, and 29.0%, respectively. For the treatment of mixed hole liquid starter fertilizer, the plant heights of MHALF100 and MHALF200 were significantly greater than those of MHALF30 and MHALF70 in 2021.

In 2022, MHALF200 exhibited significantly greater plant heights than MHALF30, MHALF70, and MHALF100. For the treatment of side hole liquid starter fertilizer, SHALF30, SHALF70, SHALF100, and SHALF200 had significantly different plant heights in both 2021 and 2022. These results indicate that the fertilizer application rate significantly affected on plant height, with taller plants observed at higher fertilizer levels. When the fertilizer rate was the same, no significant differences in plant height were observed between MHALF70, MHALF100, and MHALF200 compared to SHALF70, SHALF100, and SHALF200 in 2021. Similarly, in 2022, MHALF100 and MHALF200 did not show significant differences compared to SHALF100 and SHALF200. Additionally, the plant heights of MHALF100 and SHALF100 did not significantly differ from that of BAGF in 2022. However, in 2021, the plant heights of MHALF100 and SHALF100 significantly differed from BAGF, with increases of 3.3% and 2.2%, respectively.

At the jointing stage (Figure 5b), plant height was significantly influenced by starter fertilizer application. The treatments of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 resulted in average plant height increases of 9.3%, 9.0%, 12.5%, 16.3%, 19.6%, 7.5%, 10.1%, 15.1%, and 18.7%, respectively, compared to CK. For the treatment of both mixed and side hole liquid starter fertilizer, significant differences in plant height were observed among all treatments in both 2021 and 2022. This indicates that the fertilizer rate significantly impacted on plant height, with a higher application rate generally leading to increased plant height. When the fertilizer rate was the same, MHALF30, MHALF70, and MHALF100 exhibited plant heights 1.3%, 2.2%, and 1.0% greater, respectively, than SHALF30, SHALF70, and SHALF100. However, no significant difference was found between MHALF200 and SHALF200 in 2021. In contrast, in 2022, the plant height of MHALF200 showed a significant difference compared to SHALF200, with an increase of 0.9%. Additionally, MHALF100 and SHALF100 significantly increased plant height by 6.4% and 5.3%, respectively, compared to BAGF.

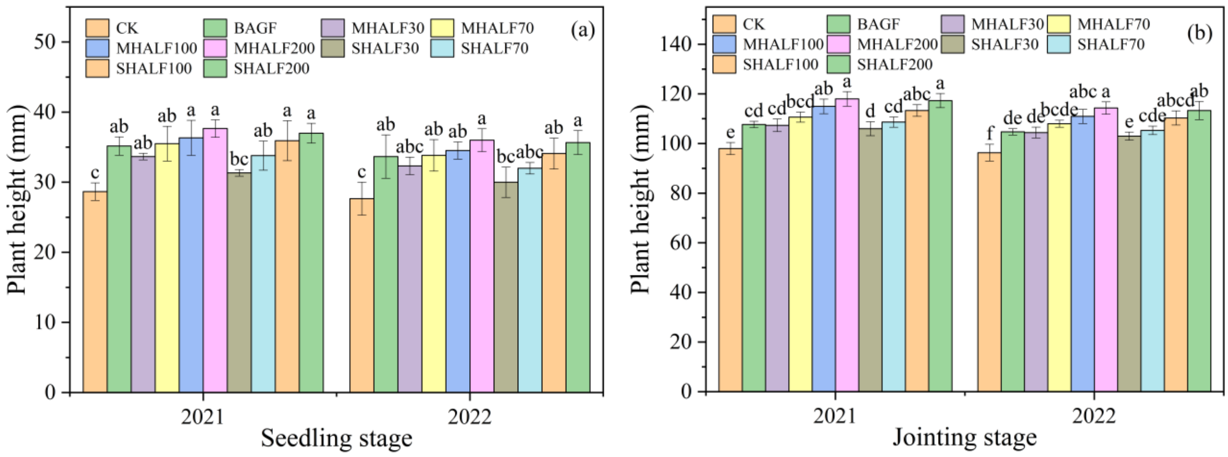

Fig. 5 - Plant height of maize under different fertilization treatments at the seedling stage (a) and jointing stage (b) in 2021 and 2022

CK: Control treatment with no starter fertilizer; BAGF: Band application of granular fertilizer; MHALF30, MHALF70, MHALF100, andMHALF200 represent the mixed hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; SHALF30, SHALF70, SHALF100, and SHALF200 represent the side hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively. Different letters above the bars indicate significant differences among treatments according to the Waller-Duncan test (P < 0.05).

Maize Yield and Yield Components

The maize yield and yield components under different fertilizer treatments in 2021 and 2022 are shown in Table 2. The analysis of variance revealed that fertilization treatment had a significant effect on maize yield ($P < 0.01$), spikes per hectare ($P < 0.01$), grains per spike ($P < 0.05$), and 1000-grain weight yield components ($P < 0.01$), whereas the effects of year and the interaction between year and treatment were not significant. Maize yield responses varied across different fertilization treatments. The treatments of BAGF, MHALF30, MHALF70, SHALF30, SHALF70, SHALF100, and SHALF200 resulted in average yield increases of 3.6%, 4.0%, 1.6%, 4.2%, 4.9%, 4.1%, and 3.9%, respectively, compared to CK. However, MHALF100 and MHALF200 led to reductions in maize yield by 1.2% and 2.9%, respectively, likely due to lower emergence rates associated with MHALF. This could be attributed to starter fertilizer promoting early maize growth and earlier flowering, while excessive rates led to lower emergence rate with mixed hole liquid fertilization. In general, the treatment of MHALF led to decreased yields as fertilization rate increased. For the treatment of side hole liquid fertilizer, no significant differences in yield were observed across different fertilization rates, except for SHALF100, in both 2021 and 2022. This suggests that while MHALF may have a negative impact on yield at higher rates, SHALF's effect on yield remains consistent, with some variation observed at certain fertilizer levels.

When the fertilizer rate was the same, the maize yields of MHALF70, MHALF100, and MHALF200 showed significant differences compared to SHALF70, SHALF100, and SHALF200 in both 2021 and 2022, with average decreases of 3.2%, 5.1%, and 6.5%, respectively. MHALF30 and SHALF30 did not show significant differences in yield in 2021. Furthermore, MHALF100 resulted in significantly lower yields than BAGF in both 2021 and 2022, with an average decrease of 5.0%. SHALF100 significantly increased yield by 1% in 2021 compared to BAGF, but no significant difference was observed in 2022. This indicates that the treatment of MHALF generally resulted in lower yields than SHALF, with some variations between the different fertilizer rates.

Table 2

The maize yield and yield components under different fertilizer treatments in 2021 and 2022

*CK: Control treatment with no starter fertilizer; BAGF: Band application of granular fertilizer; MHALF30, MHALF70, MHALF100, andMHALF200 represent the mixed hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively; SHALF30, SHALF70, SHALF100, and SHALF200 represent the side hole application of liquid fertilizer at 30%, 70%, 100%, and 200% of the BAGF treatment, corresponding to 45, 105, 150, and 300 kg/ha, respectively. Different letters above the bars indicate significant differences among treatments according to the Waller-Duncan test (P < 0.05). **, significant at P<0.01; *, significant at P<0.05; ns, not significant.*

Year	Treatment	Spikes per hectare	Grains per spike	1000-grain weight（g）	Maize yield (kg/ha)
2021	CK	57512^{a}	660^{b}	315.9^{b}	11993.0^{ab}
	BAGF	56901^{ab}	684^{ab}	322.0^{ab}	12526.5^{a}
	MHALF30	56711^{abc}	688^{ab}	320.7^{ab}	12509.6^{a}
	MHALF70	54137^{d}	690^{a}	324.0^{ab}	12106.4^{ab}
	MHALF100	52174^{e}	694^{a}	326.9^{ab}	11834.8^{ab}
	MHALF200	50680^{e}	695^{a}	327.8^{ab}	11555.3^{b}
	SHALF30	57167^{ab}	678^{ab}	320.1^{ab}	12461.3^{a}
	SHALF70	56539^{abc}	683^{ab}	325.7^{ab}	12576.3^{a}
	SHALF100	55491^{bcd}	687^{ab}	326.9^{ab}	12469.9^{a}
	SHALF200	54972^{cd}	687^{ab}	328.5^{a}	12412.6^{a}
2022	CK	57637^{a}	653^{b}	314.3^{b}	11838.4^{bcd}
	BAGF	56469^{ab}	677^{ab}	318.7^{bc}	12172.1^{abc}
	MHALF30	55378^{bc}	684^{a}	324.0^{ab}	12264.7^{ab}
	MHALF70	54114^{c}	686^{a}	326.0^{ab}	12094.8^{abcd}
	MHALF100	51482^{d}	689^{a}	329.0^{a}	11709.4^{cd}
	MHALF200	50419^{d}	697^{a}	329.7^{a}	11585.8^{d}
	SHALF30	56775^{ab}	675^{ab}	321.3^{abc}	12305.6^{ab}
	SHALF70	56467^{ab}	677^{ab}	324.7^{ab}	12422.4^{a}
	SHALF100	55488^{bc}	682^{ab}	326.3^{ab}	12350.2^{ab}
	SHALF200	55158^{bc}	683^{a}	327.3^{a}	12339.7^{ab}
ANOVA					
Year (Y)		ns	ns	ns	ns
Treatment (T)		**	*	**	**
Y×T		ns	ns	ns	ns

Starter fertilization significantly influenced the spikes per hectare. The treatments MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 resulted in average reductions in spikes per hectare of 1.5%, 2.7%, 6.0%, 10.0%, 12.2%, 1.0%, 1.9%, 3.6%, and 4.4%, respectively, compared to CK. Higher fertilization rates generally led to more pronounced reductions in spikes per hectare for both mixed and side hole liquid fertilizer treatments. When the fertilization rate was the same, the spikes per hectare in MHALF30, MHALF70, MHALF100, and MHALF200 were 1.6%, 4.2%, 6.6%, and 8.2% lower than those in SHALF30, SHALF70, SHALF100, and SHALF200, respectively. This suggests that the fertilization method significantly affected the spikes per hectare, with SHALF resulting in higher spikes per hectare than MHALF. This aligns with the trends observed in the emergence rate data, where SHALF demonstrated a more consistent or less inhibitory effect on emergence rate than MHALF. The negative impact of higher fertilization rates with MHALF could lead to reduced spike numbers, whereas SHALF seem to maintain or improve emergence rate and spike production.

Starter fertilization significantly increased the grains per spike. The treatments of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 resulted in an increase in grain numbers by 3.6%, 4.4%, 4.8%, 5.3%, 6.0%, 3.0%, 3.6%, 4.3%, and 4.4%, respectively, compared to CK. Only MHALF30 showed significant differences in grains per spike in 2021 for the treatment of mixed hole liquid starter fertilizer. For the treatment of side hole liquid starter fertilizer, only SHALF200 showed significant differences in grains per spike in 2022. When the fertilization rate was the same, MHALF70, MHALF100, and MHALF200 increased the number of grains by 1.0%, 0.9%, and 1.2% compared to SHALF70, SHALF100, and SHALF200. No significant difference was observed between MHALF30 and SHALF30 in 2021.

However, in 2022, MHALF30, MHALF70, and MHALF100 increased grains per spike by 1.3%, 1.2%, and 1.1% compared to SHALF30, SHALF70, and SHALF100. MHALF200 and SHALF200 showed no significant difference.

Starter fertilization significantly enhanced the 1000-grain weight. The treatments of BAGF, MHALF30, MHALF70, MHALF100, MHALF200, SHALF30, SHALF70, SHALF100, and SHALF200 resulted in increases in 1000-grain weight by 1.7%, 2.3%, 3.1%, 4.1%, 4.3%, 2.3%, 3.2%, 3.7%, and 4.1%, respectively, compared to CK. In 2021, except for SHALF200, all treatments of MHALF and SHALF showed no significant differences in 1000-grain weight. When the fertilization rate was the same, MHALF30 and MHALF100 showed significant differences compared to SHALF30 and SHALF100 in 2022, with increases of 0.8% and 0.8%, respectively.

CONCLUSIONS

This study aimed to investigate the effects of different liquid starter fertilizer placements and rates on maize emergence, early growth, and yield under cold temperate conditions. The findings demonstrate that the placement of liquid starter fertilizer plays a critical role in determining maize emergence and early growth. In particular, SHALF at moderate rates (45 and 105 kg/ha) significantly improved emergence rate, dry matter mass, and plant height compared to MHALF and BAGF. In contrast, high fertilization rates (150 and 300 kg/ha) in MHALF treatments negatively impacted emergence rate. Fertilizer treatment also had a significant effect on maize yield and yield components. The SHALF70 treatment resulted in an average yield increase of 4.9% compared to CK. These results indicate that moderate rate of SHALF provides a practical and effective strategy for improving maize productivity in cold temperate regions. However, this study primarily focused on physical growth parameters such as emergence rate, dry matter mass, and plant height, without evaluating nutrient uptake efficiency or physiological indicators. These factors are critical for understanding how different fertilization treatments influence plant metabolic processes and overall nutrient use efficiency. Future research should incorporate assessments of soil nutrient dynamics and tissue nutrient profiling to better understand the mechanisms of treatment effects and to optimize fertilizer strategies for maize production under varying environmental conditions.

ACKNOWLEDGEMENT

This research was funded by the National Natural Science Foundation of China, grant number 32501802; the Science and Technology Project of Henan, grant number 242102111176; the Postdoctoral Research Funding Program of Henan, grant number 24XM0495; China Agriculture Research System of MOF and MARA, grant number CARS-04.

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